



(51) International Patent Classification:

C21D 6/00 (2006.01) G16C 10/00 (2019.01)

C21D 11/00 (2006.01) G16C 60/00 (2019.01)

(21) International Application Number:

PCT/IB2023/056772

(22) International Filing Date:

29 June 2023 (29.06.2023)

(25) Filing Language:

English

(26) Publication Language:

English

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(81) Designated States (unless otherwise indicated, for every kind of national protection available): AE, AG, AL, AM, AO, AT, AU, AZ, BA, BB, BG, BH, BN, BR, BW, BY, BZ, CA, CH, CL, CN, CO, CR, CU, CV, CZ, DE, DJ, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IQ, IR, IS, IT, JM, JO, JP, KE, KG, KH, KN, KP, KR, KW, KZ, LA, LC, LK, LR, LS, LU, LY, MA, MD, MG, MK, MN, MU, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PA, PE, PG, PH, PL, PT, QA, RO, RS, RU, RW, SA, SC, SD, SE, SG, SK, SL, ST, SV, SY, TH,

TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, WS, ZA, ZM, ZW.

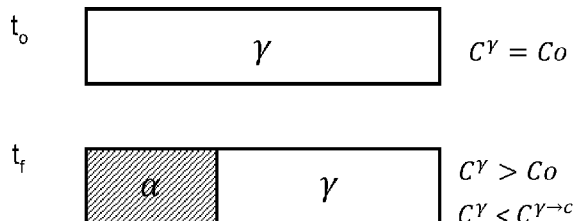
(84) Designated States (unless otherwise indicated, for every kind of regional protection available): ARIPO (BW, CV, GH, GM, KE, LR, LS, MW, MZ, NA, RW, SC, SD, SL, ST, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, RU, TJ, TM), European (AL, AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV, MC, ME, MK, MT, NL, NO, PL, PT, RO, RS, SE, SI, SK, SM, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, KM, ML, MR, NE, SN, TD, TG).

Published:

— with international search report (Art. 21(3))

(54) Title: METHOD FOR DETERMINING AN AMOUNT OF BAINITIC FERRITE FORMED DURING A STEEL PROCESSING OPERATION, ASSOCIATED MONITORING OR CONTROL METHODS

FIG 1



(57) Abstract: The method comprises: - s1) determining a bainitic ferrite growth rate proportional to: $\exp(-Q^*/RT)$, Q^* being an activation energy for an austenite to bainitic ferrite transformation, and proportional to a moderation coefficient which approaches zero when a free enthalpy of a bainitic ferrite phase approaches a free enthalpy of an austenite phase that depends on a Carbon content (C^γ) in the austenite phase, - s2) determining a cementite growth rate, depending at least on the Carbon content in the austenite phase, - s3) determining values at a next time step for bainitic ferrite, austenite and cementite phases fractions (f_α, f_γ, f_c), based on the bainitic ferrite growth rate and on the cementite growth rate, and updating the Carbon content in the austenite phase based on the values of said phases fractions.



Method for determining an amount of bainitic ferrite formed during a steel processing operation, associated monitoring or control methods

The technical field concerns phase transformation determination, for a steel semi-product undergoing a steel processing operation, in particular bainitic ferrite formation prediction. Such a prediction is useful in particular for monitoring, controlling, designing or tuning such a steel processing operation.

Technical background

Recent developments in steel for automotive and other applications lead to consider bainite microstructures as good candidates to provide an alternative balance of strength and ductility. Being able to determine how much bainite is being formed in a steel undergoing cooling, or more generally undergoing a thermal treatment, is thus very useful, to better control the bainite content of the steel finally obtained. Being able to determine the bainite growth rate in a steel is also very useful for the control of a cooling operation itself, or for the control of a thermal treatment. Indeed, as the bainite formation is exothermal, taking into account how much bainite is being formed enables a more accurate temperature control.

Regarding bainite formation, different models have been developed in the last years to predict Time-Temperature-Transformation (TTT) curves, or to predict bainite formation kinetics and final fractions. Some of these models perform well for so called 'carbide free' grades (for which there is no or little cementite formation due to high Silicon or Aluminium content), but less accurately for grades with a low silicon content. Other models predict well bainite formation for lean-silicon steels, where there may be substantial carbide precipitation, but less accurately for carbide free grades (in particular regarding the final bainite fraction).

In this context, there is a need for a method enabling to determine how much bainite is being formed in a steel whose temperature is lowered below the bainite start temperature T_B , both for 'carbide-free' grade and lean-silicon ones, and with a good compromise between computing time and accuracy.

Summary of the invention

The invention is achieved by providing a method according to claim 1.

In the computation of the bainitic ferrite formation, the moderation coefficient employed in the claimed method enables to slow down this formation when the free enthalpy in the bainitic ferrite phase approaches the free enthalpy in the austenite phase. This enables to obtain final bainitic ferrite fractions that are in good agreement with experimental results, for

'carbide-free' grades. Besides, this moderation coefficient does not modify substantially the dynamic of formation, when the difference between said free enthalpies is substantial, at the beginning of bainite formation. This enables to obtain also good agreements regarding the formation kinetics.

5 This moderation coefficient mainly reflects a carbon-content driven equilibrium between the bainitic ferrite phase and the austenite phase. For lean-silicon steels, cementite precipitation modifies the carbon content in the austenite phase, and thus modifies the equilibrium in question. Taking into account this carbon-content driven equilibrium (through the moderation coefficient) together with cementite formation (should cementite precipitates) then
10 enables to predict final bainitic ferrite fractions that are in good agreement with measurements, both for carbide-free grades and for grades with lower silicon contents.

The method can also comprise features of anyone of claims 2 to 10, taken alone or in combination.

The invention concerns also a method for monitoring or controlling a steel processing
15 installation, according to any of claim 11 to 17. It also concerns an electronic device according to claim 18. The invention also concerns a computer program according to claim 19, to be executed on a computer (said computer being connected to a temperature sensor, actuators or a human-computer interface of the steel processing installation, or a production database, when appropriate, depending on the details of the method executed by said computer).

20 Detailed description

The invention will now be described in detail and illustrated by examples without introducing limitations, with reference to the appended figure:

- Figure 1 schematically represents phases fractions in a steel at an initial and final time of a phase transformation,

25 - Figure 2 schematically represents phases fractions in a steel at different times of another phase transformation,

- Figures 3 to 5 represent test results, together with calculations results determined according to the invention, for isothermal transformations, for three Carbide-Free-Bainite exemplary grades,

30 - Figure 6 represents test results, plotted against calculations results, for some lean-silicon grades,

- Figure 7 represents test results, plotted against calculations results determined according to the invention, for these lean-silicon grades,

- Figure 8 and 9 gather test results, both for Carbide-Free-Bainite grades and for lean-silicon
35 grades, plotted against calculation results,

- Figure 10 schematically represents steps executed to determine an amount of bainitic ferrite formed during a steel processing operation, according to an embodiment of the invention,

- Figure 11 schematically represents steps executed to determine an amount of bainitic ferrite formed during a steel processing operation, according to another embodiment,
- Figure 12 schematically represents a steel processing installation, to be monitored or controlled using a method according to the invention,
- 5 - Figure 13 and 14 gather production data, for production carried on the steel processing installation of figure 12, using either a control method according to the invention, or a control method of the prior art.

Bainite formation

10 In the methods and devices according to the invention, an amount of bainitic ferrite formed in a steel semi-product during a steel processing operation is determined by executing the following steps:

- acquiring a chemical composition CC of the steel of said steel semi-product,
- 15 - s1) determining a bainitic ferrite growth rate, as being proportional to:
 - o a density of bainitic ferrite nucleation centers $n_{nucl,\alpha}$, to
 - o $\exp(-Q^*/RT)$ where T is the temperature of the steel, R is the universal gas constant and Q^* is an activation energy for an austenite to bainitic ferrite transformation, and to
 - 20 o a moderation coefficient C_{mod} , which approaches zero when a free enthalpy of a bainitic ferrite phase α approaches a free enthalpy of an austenite phase γ , the enthalpy of the austenite phase depending at least on a Carbon content C^γ in the austenite phase γ ,
- s2) determining a cementite growth rate, depending at least on the chemical
- 25 composition CC of the steel and on the Carbon content C^γ in the austenite phase,
- s3) determining values at a next time step for bainitic ferrite, austenite and cementite phases fractions f_α , f_γ and f_C , based on the bainitic ferrite growth rate and on the cementite growth rate, and determining a value at the next time step for the Carbon content in the austenite phase C^γ , based on the values of the phases
- 30 fractions f_α , f_γ , f_C .

35 The set of steps s1, s2 and s3 is executed several times successively, to determine gradually the temporal evolution of the bainitic ferrite content in said steel, during the steel processing operation in question, while taking into account, at each time step, possible Carbon redistribution among the three possible phases mentioned above (through the calculation of the updated value, at each time step, of the Carbon content in the austenite phase C^γ), and the influence of this redistribution on the bainitic ferrite and cementite growth rates.

Figure 1 represents schematically phases fractions in a steel at an initial time t_0 and final time t_f of a phase transformation, occurring at a temperature below the Bainite start temperature T_B (and above the Martensite start temperature T_M), for a steel with a high Silicon content (for instance 1.5 weight % or above), of the CFB type (Carbide-Free Bainite type). At the initial time t_0 , it is considered, in this simplified example, that austenite only is present, with an initial Carbon content in the austenite phase $C^\gamma = C_o$. Some bainitic ferrite then forms, until the transformation stops (because an equilibrium is reached, in this case), at time t_f . During this transformation, the Carbon is redistributed: it is rejected from the bainitic ferrite phase α (where the Carbon content C^α is negligible compared to the carbon content C^γ in the austenite phase) into the austenite phase γ . The Carbon content in the austenite phase, C^γ , thus gradually increases.

When computing the bainitic ferrite growth rate as described above, the moderation coefficient C_{mod} enables to slow down the bainitic ferrite formation when the Carbon content in the austenite phase increases, in the course of the transformation, and enables then to obtain final fractions of non-transformed austenite (that are not null, for CFB grades), that are in good agreement with experimental results.

The difference between the free enthalpy of a bainitic ferrite phase and the free enthalpy of the austenite phase is noted as $\Delta G_{\gamma \rightarrow \alpha}$. It is a free enthalpy change for diffusion less transformation from austenite to bainitic ferrite.

Here, the moderation coefficient C_{mod} is approximately proportional to $|\Delta G_{\gamma \rightarrow \alpha}|/RT$ when $|\Delta G_{\gamma \rightarrow \alpha}|/RT$ approaches zero (for instance, proportional or even equal to $|\Delta G_{\gamma \rightarrow \alpha}|/RT$, within 5% or less when $|\Delta G_{\gamma \rightarrow \alpha}|/RT$ is smaller than 0.2). This enables to slow down substantially the bainitic ferrite formation when $\Delta G_{\gamma \rightarrow \alpha}$ approaches zero. Besides, the moderation coefficient C_{mod} is bound, limited to a constant value when $|\Delta G_{\gamma \rightarrow \alpha}|/RT$ has a high value (eg: higher than 2). This prevents the moderation coefficient from modifying the bainite formation kinetics, at the beginning of the transformation, and enables obtaining good agreement with experimental results regarding the formation kinetics.

To fulfill these criteria, the moderation coefficient C_{mod} is for instance calculated as being equal to $\tanh(|\Delta G_{\gamma \rightarrow \alpha}|/RT)$.

Figure 2 represents schematically phases fractions in a steel, at an initial time t_0 , a final time t_f and two intermediary times t_1 and t_2 of a phase transformation (with $t_f > t_2 > t_1 > t_0$). This transformation occurs at a temperature below the Bainite start temperature T_B (and above the Martensite start temperature T_M), for a steel with a very low Silicon content (for instance less than 0.1 weight %), in which cementite (carbide) precipitation is likely. At the initial time t_0 , only the austenite phase γ is present, with an initial Carbon content $C^\gamma = C_o$. Some bainitic ferrite α then forms and some carbon is thus rejected in the austenite phase where the carbon content

C^Y increases until this carbon content reaches (at time t_1) a Carbon content threshold $C^{Y \rightarrow C}$ for cementite precipitation. The cementite phase C then grows up (time t_2). As the carbon content C^C in the cementite phase is high (around 6.67 weight %), cementite formation has a pumping action regarding the carbon content C^Y , and tends to drastically reduce the carbon content C^Y in the austenite phase. So, as C^Y remains low, the moderation coefficient C_{mod} remains non-zero, non-negligible, and the austenite to bainitic ferrite transformation continues until no more austenite is present (at time t_f).

In the method presented above, taking into account that cementite may form during the steel processing operation, depending on the chemical composition CC of the steel, the cementite formation then pumping carbon from the austenite phase, enables to predict adequate final bainitic ferrite fractions, both for carbide-free grades and for grades with low silicon and aluminum contents (for which the final, remaining austenite phase fraction is usually very low, or even null).

In step s2, the cementite growth rate may remain equal to zero all along the steel processing operation, depending on the chemical composition CC of the steel (in particular for chemical compositions with high Silicon or Aluminum content). Or, on the contrary, it may become non-null during the transformation, for chemical compositions with low Silicon and Aluminum content. In particular, the cementite growth rate may be kept equal to zero as long as the Carbon content in the austenite phase, C^Y , remains below the Carbon content threshold for cementite precipitation, $C^{Y \rightarrow C}$, above mentioned.

Bainite is a microstructure comprising of very thin ferrite plates, possibly separated by retained austenite. It forms in austenite. The ferrite of these thin ferrite plates is designated as bainitic ferrite (or more simply as bainite), in this document. When cementite forms, it is assumed here that it forms in the austenite (and then has the carbon-pumping action, with respect to the austenite, as above described with reference to figure 2).

The steel processing operation, for which the amount of bainitic ferrite is determined, is a processing operation for which bainite is likely to form. It is typically a processing operation:

- for which the steel is, for some time, at high temperature, typically above AC3 temperature, and then contains as substantial fraction of austenite, for instance more than 50%wt or even more than 70%wt of austenite, the rest being mainly ferrite,

- or for which the steel initially contains such a substantial fraction of austenite (the rest being mainly ferrite).

Then, during this processing operation, the temperature of the steel is decreased and becomes lower than the Bainite start temperature T_B . Bainite then forms, its kinetics of formation being determined as above explained.

The gradual calculation of the temporal evolution of the phases fractions f_α , f_γ , f_C starts with initial conditions that are typically $f_\gamma(t = 0) = f_{\gamma 0}$, $f_\alpha(t = 0) = 0$ and $f_C(t = 0) = 0$, with $f_{\gamma 0} = 1$ if the steel initially contains 100% austenite (and no ferrite). This gradual, iterative calculation may be carried on until an end point of the transformation. This end point may correspond to a situation where said phases fractions reach constant, steady-state values (i.e.: a 'statis', corresponding to the final time t_f of figures 1 and 2), or to an instant the steel processing operation ends (output of the steel semi-product from a steel processing installation where it is processed, for instance).

The steel processing operation in question may be a hot rolling operation, including a steel cooling operation achieved on a Run Out Table, for instance.

The steel semi-product can be a steel strip or sheet, a slab, a billet, a broom, an ingot, a bar, a beam, a tube or a wire. More generally, the steel semi-product is an intermediary source-product, destined, subsequently, to manufacture a part, a good or a construction.

The chemical composition CC of the steel, taken into account to determine the amount of bainitic ferrite being formed, may be specified by the weight% of the different alloy elements present in said steel, for instance the weight % of C, Mn, Si, Al, Cr, Cu, Mo, Ni. These alloy elements contents are the initial contents in the steel, at the beginning of the steel processing operation. The carbon content, defining said chemical composition CC, may be, more specifically, an initial carbon content in the austenite. It is C_0 .

If a ferritic transformation occurred, before the bainitic transformation herein modeled starts, the ferrite fraction f_F is nonzero, and the initial austenite fraction $f_{\gamma 0}$ is below 1. In such a case, the initial carbon content C_0 , in the austenite phase, is calculated as being equal to $C_{ini}/f_{\gamma 0}$, where C_{ini} is the carbon content in the steel before the ferritic transformation occurred (in other words, C_{ini} corresponds to the average, global carbon content of the steel; to its global chemistry).

The computation steps, described below in more detail, are adequate to compute an amount of bainitic ferrite (in other words, an amount of bainite) formed during a steel processing operation. They can be combined with additional steps to further take into account the possible formation of other types of phases.

In the instant method for determining the amount of bainitic ferrite being formed during such a steel processing operation, the carbon content, either in the austenite, bainitic ferrite, or cementite phase, may be expressed as a weight proportion (weight %) in said phase, as a mass concentration, as a molar concentration, or any other quantity representative of the density of carbon in said phase. Regarding the phase fractions mentioned above, they are volume fractions, here.

Step s1: determination of the bainitic ferrite growth rate

In the method here described, the bainitic ferrite growth rate is computed according to equation eqn 1 below:

$$\frac{d f_{\alpha}}{dt} = \nu \cdot n_{nuc\ell,\alpha} \cdot f_{\gamma} \cdot (1 + \lambda f'_{\alpha}) \cdot \exp(-Q^*/RT) \cdot C_{mod} \quad (eqn 1)$$

5 where

- f_{α} is the volume fraction of bainitic ferrite in the steel,
- $\nu = kT/h = 10^{13} s^{-1}$ (k being the Boltzmann constant, and h being the Planck constant),
- λ is an auto-catalysis coefficient proportional to a dimension d_{γ} of austenite grains,
- 10 and
- f'_{α} is equal to f_{α} , or possibly to $f_{\alpha} + f_F$.

The term f_{γ} (for instance equal to $(1 - f_{\alpha})$ in the absence of cementite and in the absence of ferrite – that is if $f_F = 0$) reflects that the number of possible nucleation sites decreases gradually as the amount of austenite decreases, when bainitic ferrite forms.

15 The auto-catalysis coefficient λ is expressed as $\lambda = a \cdot d_{\gamma}$. For the steel grades considered here (whose alloys elements contents are comprised in the ranges specified further below), a value of 'a' from $0.1 \mu m^{-1}$ to $0.8 \mu m^{-1}$, or even from 0.1 to $0.5 \mu m^{-1}$ is adequate.

In the instant model, the density of bainitic ferrite nucleation centers $n_{nuc\ell,\alpha}$ is computed according to the following equation:

$$20 \quad n_{nuc\ell,\alpha} = \alpha^b \cdot (T_B - T)$$

where α^b is a quantity related to a density of defects at grains boundaries, favourable to bainitic ferrite growth. α^b depends on the chemical composition CC of the steel, and on the austenite grains dimension d_{γ} , but does not depend on the temperature T, nor on the instant Carbon content C^{γ} in the austenite phase. α^b may more specifically be determined according to the equation below (where d_{γ} is expressed in meters):

$$\alpha^b = \alpha^m \cdot Kst / d_{\gamma}$$

25 where α^m is a rate parameter for martensite formation, depending on the steel chemical composition CC and where Kst is a constant coefficient, from $1 \cdot 10^{-9}$ to $100 \cdot 10^{-9}$ meters. α^m may more specifically be determined according to the following equation, where α^m is expressed in K^{-1} :

$$\alpha^m = (27.2 - 0.14 x_{Mn} - 0.08 x_{Ni} - 0.11 x_{Cr} - 0.05 x_{Mo} + 0.21 x_{Si} - 19.8 [1 - \exp(-1.56 C_o)]) / 1000$$

30 where x_{Mn} , x_{Ni} , x_{Cr} , x_{Mo} , x_{Si} and C_o are, respectively, the Manganese, Nickel, Chromium, Molybdenum, Silicon, and Carbon contents for said chemical composition CC, expressed in weight %.

Regarding the activation energy Q^* for the austenite to bainitic ferrite transformation, it is calculated here as being equal, or substantially equal to $Q_o + K_1 \cdot |\Delta G_{\gamma \rightarrow \alpha}|$, and where Q_o and K_1 may depend on the chemical composition CC of the steel but remain constant when the Carbon content C^γ in the austenite phase varies with time, during the phase transformation of the steel. By substantially equal it is meant equal within 10%, or even within 5% or 3%. The inventors have noticed that this way to compute Q^* leads to a good agreement between the model predictions and experimental observations, in terms of kinetics and final phases fractions. Besides, this formulation has the advantage to isolate a part of Q^* that varies with C^γ and has thus to be recalculated at each time step (namely $\Delta G_{\gamma \rightarrow \alpha}$), from a part of Q^* independent of C^γ (namely Q_o). Besides, the term varying with C^γ is the same as the one in the moderation coefficient C_{mod} , and has thus to be calculated just once when determining the bainitic ferrite growth rate, thanks to this particular way to express Q^* . In practice, the value of Q_o is typically comprised between 150 and 200 kJ/mol. And the value of K_1 is from 3 to 10, or even from 5 to 7.

Quantity Q_o depends on the chemical composition CC of the steel. The inventors have observed that the dependence of Q_o with the chemical composition CC can be taken into account conveniently by computing Q_o as being equal, or substantially equal to $A+B \cdot (T-T_M)$, A and B being two constants and T_M being the Martensite start temperature. In other words, the inventors have noticed that this expression fits well the values of Q_o . In this expression, the dependency of Q_o with the chemical composition CC is reflected by the dependency of T_M with the chemical composition CC, dependency for which numerous data and studies are available. In practice, the value of constant A is typically comprised between 160 et 200 kJ/mol while the value of B is typically comprised between 100 and 150 J/(mol.K). For instance, the tests presented below, with reference to the figures, are carried on with $A=177$ kJ/mol, $B=120$ J/(mol.K) and $K_1=6$.

For a given chemical composition, the value of the Martensite start temperature T_M can be experimentally determined by dilatometry. It can also be found in data from the literature. It can also be determined using the following equation (valid for the alloy elements content ranges defined further below), where T_M is in Celsius degrees ($^{\circ}\text{C}$):

$$T_M = 565 - 31 \cdot x_{Mn} - 13 \cdot x_{Si} - 10 \cdot x_{Cr} - 18 \cdot x_{Ni} - 12 \cdot x_{Mo} - 600 \cdot (1 - \exp(-0.96 \cdot x_C))$$

Similarly, the value of the Bainite start temperature T_B can be experimentally determined by dilatometry and microstructural analysis, or found in data from the literature. It can also be determined using the following equation (valid for the alloy elements content ranges defined further below), where T_B is in $^{\circ}\text{C}$:

$$T_B = 839 - 86 \cdot x_{Mn} - 23 \cdot x_{Si} - 67 \cdot x_{Cr} - 33 \cdot x_{Ni} - 75 \cdot x_{Mo} - 270 \cdot (1 - \exp(-1.33 \cdot C_o))$$

where x_{Mn} , x_{Si} , x_{Cr} , x_{Ni} , x_{Mo} and C_o , are, respectively, the Manganese, Silicon, Chromium, Nickel, Molybdenum and Carbon contents corresponding to the chemical composition CC of the steel, expressed in weight %.

Regarding the austenite grains dimension d_γ , taken into account to compute the bainite growth rate, it may be measured, on a sample taken from the steel semi-product before its processing, or taken from another semi-product of a same group of semi-products (produced during a same production campaign). Alternatively, the grains dimension d_γ may also be calculated, based on the characteristics of previous processing underwent by the steel semi-product (underwent before the instant steel processing operation). It could also be determined, based on these previous process characteristics, using a look-up-table. Anyhow, the grains dimension d_γ is defined, as usual in this technical field, as a kind of average diameter of the grains. From a geometric point of view, it is determined using the so-called intercepts method: in an image of the sample, a number of vertical and horizontal lines are drawn; then, each time a line passes over a grain boundary, the dimension (width) of the grain along this line is determined. A vertical and a horizontal average are thus obtained. The average of these two averages is the grain dimension d_γ .

Taking into account the expressions employed here for $n_{nuc\ell,\alpha}$ and Q^* , the bainite growth rate reads (eqn 1a):

$$\frac{d f_\alpha}{dt} = v \cdot \alpha^b \cdot (T_B - T) f_\gamma (1 + \lambda f'_\alpha) \cdot \exp(-Q_o/RT) \cdot \exp(-K_1 \cdot |\Delta G_{\gamma \rightarrow \alpha}|/RT) \cdot \tanh(|\Delta G_{\gamma \rightarrow \alpha}|/RT) \quad (eqn 1a)$$

In equation eqn 1a, the quantities that vary, or that may vary during the transformation, and whose values are updated at each time step, are:

- the bainitic ferrite phase fraction f_α ,
- the temperature T (which may change during the transformation),
- and $\Delta G_{\gamma \rightarrow \alpha}$, whose variations are mainly caused by the variation of the Carbon content in the austenite phase, C^γ .

Remarkably, the other parameters of eqn 1a remain constant during the transformation.

Regarding $\Delta G_{\gamma \rightarrow \alpha}$ (which varies with variation with C^γ), it is computed by calculating:

- a free enthalpy for a single austenitic phase, given the carbon content C^γ in that phase, and for other elements contents, like x_{Mn} , x_{Si} , x_{Mo} , ..., given the chemical composition CC of the steel),
- a free enthalpy for a single ferritic phase, given the elements contents (x_{Mn} , x_{Si} , x_{Mo} , ...) specified by the chemical composition CC of the steel,
- and subtracting one from the other.

These values of free enthalpy may be calculated using commercial thermodynamic calculations software, like ThermoCalc software, for instance.

Step s2: determination of the cementite growth rate

As above explained, the cementite growth rate is kept equal to zero as long as the Carbon content in the austenite phase, C^γ , is below the Carbon content threshold for cementite precipitation, $C^{\gamma \rightarrow c}$.

Once the Carbon content in the austenite phase C^γ has passed the threshold in question, cementite forms from the austenite.

The carbon content threshold for cementite precipitation, $C^{\gamma \rightarrow c}$, can be determined according to the following article: "Effect of partitioning of Mn and Si on the growth kinetics of cementite in tempered Fe–0.6 mass% C martensite", by Miyamoto, J.C. Oh, K. Hono, T. Furuhashi, and T. Maki, Acta Materialia, Volume 55, Issue 15, 2007, Pages 5027-5038. In particular, table 5 of this article provides values for enthalpies of formation of M_3C compounds (M being an alloy element present in the steel, like Si, or Cr), from which the free enthalpy ΔrG of formation of cementite in austenite can be calculated, for the steel considered (depending on the chemical composition CC, and with a preequilibrium hypothesis), which enables to determine the carbon content threshold for cementite precipitation, $C^{\gamma \rightarrow c}$. As a matter of example, figure 10 of this article provides limits ("PE" line in figure 10 a and b, for "ParaEquilibrium", which is assumed here), in terms of carbon concentration, for the existence of the cementite phase (θ), as a function of the Si or Mn content.

The cementite growth rate can be calculated according to the following article: "Modelling upper and lower bainite transformation in steels" by M. Azuma, N. Fujita, M. Takahashi, T. Lung, ISIJ International, vol. 45 (2005), n°2, pp 221-228, in particular as described in section 3.3 and 3.4 of that article. The information regarding cementite nuclei growth, presented in the preceding article by Miyamoto (see table 4, and eqn 2 to 4 of Miyamoto's article) can also be used for cementite growth calculation.

Step s3: determination of the carbon content in the austenite phase

In step s3, the Carbon content in the austenite phase, C^γ , is computed while neglecting a Carbon content in the bainitic ferrite phase C^α with respect to C^γ , and with a constant carbon content in the cementite phase C^c , equal to 6.67 weight%.

Taking into account the conservation of the overall quantity of Carbon initially present, C^γ is then computed according to the equation below:

$$C^\gamma = \frac{C_o - f_\alpha \cdot C^\alpha - f_c \cdot C^c}{f_\gamma} \cong \frac{C_o - f_c \cdot C^c}{f_\gamma}$$

with $f_\gamma = 1 - f_\alpha - f_c$, or possibly $= f_\gamma(t_o) - f_\alpha - f_c$.

The validity domains, for the above calculation method (both for the bainitic ferrite and cementite formation) are the followings, expressed in weight%:

- 5 - $C_o \leq 0.5$ or even ≤ 0.3 , ≤ 0.25 , or ≤ 0.2
- $x_{Mn} \leq 3$ or even ≤ 2.5 , or ≤ 2
- $x_{Si} \leq 2$, or even 1.5
- $x_{Al} \leq 1.5$
- $x_{Cr} \leq 4$, or even ≤ 1 , or ≤ 0.8
- 10 - $x_{Mo} \leq 0.8$ or even ≤ 0.5
- $x_{Ni} \leq 2$.

The numerical formulas above, for instance the formulas enabling to compute T_B or T_M , provide valid predictions, in the ranges mentioned above. And the overall method, for determining the amount of bainite formed, leads to reasonably accurate predictions, within
15 these ranges, as illustrated by the exemplary experimental test results presented below.

Exemplary test results

Carbide Free Bainite steel grades

20 Experimental tests corresponding to steel grades with a high Silicon or Aluminium content, for which carbide precipitation does not occurred (or occurred very slowly during the transformation) are presented in figures 3 to 5, and also in figures 8 and 9.

The transformations considered are isothermal transformations.

The chemical compositions, isothermal temperatures and grain sizes for these grades
25 are gathered in table 1. For each composition, the rest of the composition (in addition to the elements already specified in table 1) is iron and unavoidable impurities resulting from the smelting. The carbon content specified in table 1 is the initial content of Carbon in the austenite, C_o . No ferritic transformation occurred in the steel, before these bainitic (isothermal) transformations. The measurements of the bainitic ferrite fraction f_α are carried on by
30 synchrotron measurements.

Grade ref (1)	Grade ref (2)	transformation temperature T (°C)	dy (µm)	C%	Mn %	Cr %	Si %	Al %
g1	0.1C 2.5Mn 0.8Cr 1.5Si	430; 480	27	0.1	2.50	0.8	1.5	0
g2	0.2C 2.5Mn 0.8Cr 1.5Si	380; 430	30	0.2	2.50	0.8	1.5	0
g3	0.3C 2.5Mn 0.8Cr 1.5Si	330; 380	32	0.3	2.50	0.8	1.5	0
g4	0.3C 2.5Mn 1.5Si	400	16	0.3	2.50	0	1.5	0
g5	0.1C 2Mn 1.5Si	500; 550	50	0.11	2.10	0	1.4	0

g6	0.25C 2.1Mn 1.5Al	400; 450; 500; 550	56	0.25	2.07	0	0	1.5
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Table 1: CFB tested grades

Figures 3, 4 and 5 represent the evolution of the bainitic ferrite fraction f_{α} over time t (in seconds) for the grades g2, g5 and g4 of table 1 respectively, and for respective isothermal transformation temperatures of 380°C, 550°C and 400°C.

5 In figures 3 to 5, the measured values are represented by the plain-line curve, while the values predicted according to the above-described method are represented by the dashed line. The dotted line corresponds to predictions calculated without the moderation coefficient (that is, with by replacing the moderation coefficient by 1).

10 Figures 3 and 4 illustrate that using the moderation coefficient C_{mod} improves the prediction accuracy regarding the final bainitic ferrite fraction, compared to predictions carried on without taking into account this moderation effect. Figures 3 to 5 illustrate also that acceptable, or even good agreements are also obtained for the formation kinetics, using the computation method presented above.

15 Grades with cementite (carbide) precipitation

The test results presented in figures 6 et 7 correspond to steel grades with a low Silicon content, of 0.01wt% or less, for which carbide precipitation occurred during the transformation. The transformations considered are isothermal transformations.

20 These grades have been homogenized at 1200°C for 72 hours then air cooled. Ferrite-Pearlite microstructures are then formed at ambient temperature, and a specific treatment (with a double annealing, first at 890°C for 1 minute, then at 1100°C for 1 minute) has been applied to erase as much as possible the initial microstructure and form a relatively homogeneous microstructure with big austenite grain size before setting the temperature to the isothermal test temperature to test bainite formation. The grain sizes specified in table 2 are the one
25 employed for the bainitic transformation calculation. Measured grain sizes were of 50 microns in average, comprised between 35 and 60 microns, for these tests.

No ferritic transformation occurred in the steel, before the bainitic (isothermal) transformations presented below.

30 The chemical compositions, isothermal temperatures and grains size for these grades are gathered in table 2.

Grade ref (1)	Grade ref (2)	Isothermal transformation temperature T (°C)	d _y (μm)	C wt%	Mn wt%	Si wt%
g7	0.12C 2Mn	450; 500; 550; 600	50	0.12	2.00	0.01
g8	0.1C 2Mn	500; 525; 550; 575; 600	50	0.09	2.01	0.01
g9	0.1C 3Mn	425; 450; 475; 500; 525	50	0.09	2.98	0.01
g10	0.2C 1.5Mn	500; 525; 550; 575; 600; 625	50	0.18	1.46	0.01
g11	0.3C 1.5Mn	500; 525; 550; 575; 600	50	0.26	1.46	0.01

g12	0.3C 2Mn	500; 525; 550; 575	50	0.27	1.97	0.01
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Table 2: tested grades with possible cementite precipitation

Figures 6 and 7 represent the total fraction of austenite that has transformed during the transformation (that is $f_Y(t_o) - f_Y(t_f)$, here equal to $1 - f_Y(t_f)$), once statis is reached, expressed in %. In figure 7, the measured fraction (ordinate axis) is plotted against the fraction computed according to the method presented above (abscissa axis). In figure 6, the measured fraction (ordinate, vertical axis) is plotted against a computed fraction (abscissa, horizontal axis) computed according to the method presented above but without taking into account possible cementite formation, that is without step s2. In each figure, the straight line ($y=x$) corresponds to ideally accurate predictions.

In figure 6, for the test results surrounded by a dashed line, austenite is completely transformed into bainitic ferrite and cementite during the transformation, in practice, while the model of figure 6 (which does not take cementite formation into account) predicts only a partial transformation of the austenite. On the contrary, the model of figure 7 (which corresponds to the computation method presented in detail above) adequately predicts a full austenite transformation, in good agreement with the experiments, for the tests in question, thus illustrating the usefulness of step s2 and of carbon redistribution calculation. More generally, figure 7 shows that the method presented above, for determining the amount of bainitic ferrite (and cementite) formed during a transformation leads to final fractions in good agreement with the experiments. For the high Mn content test (grade g9), the agreement is not as good as for the other tests. So, for non-CFB grades, if a high accuracy is requested, the method in question may preferably be employed for Mn contents equal to or lower than 2.5wt%, or even equal to or lower than 2wt% (rather than on the whole range $x_{Mn} \leq 3 \text{ wt\%}$).

CFB and non-CFB grades global results

Figures 8 and 9 gather test results, both for the CFB grades g1 to g5 presented above, and for the non-CFB grades g7 to g12.

Figure 8 represents the total fraction of austenite that has been transformed during the transformation (that is $f_Y(t_o) - f_Y(t_f) = 1 - f_Y(t_f)$), once statis reached, expressed in %. Like for figure 7, the measured fraction (ordinate axis) is plotted against the fraction computed according to the method presented above (abscissa axis).

Figure 9 concerns the transformation kinetics. It represents the time $t_{50\%}$ to reach 50% of the final fraction of transformed austenite, expressed in seconds. The measured $t_{50\%}$ (ordinate axis) is plotted against the value of $t_{50\%}$ obtained using the computation method presented above (abscissa axis).

In figures 8 and 9, the straight line ($y=x$) corresponds to ideally accurate predictions.

Figure 8 shows that the method presented above, for determining the amount of bainitic ferrite formed during a transformation, leads to final fractions in good agreement with the experiments, for CFB grades as well as for grades with very low Si and Al content.

Figure 9 shows that the formation kinetics is reasonably well predicted by this method, both for CFB grades and for grades with very low Si and Al content, for response times spanning over three orders of magnitude. Still, it is observed that the predicted kinetics is usually slower than the observed one, specifically for non-CFB grades with a high carbon content (0.3wt%), namely grades g11 and g12. So, for non-CFB grades, if a high accuracy is requested, the method in question may preferably be employed only for Carbon contents equal to or lower than 0.25wt%, or even equal to or lower than 0.2wt% (rather than on the whole range $C_0 \leq 0.5 \text{ wt\%}$).

Test results for grade g6, which contains Aluminum (1.5wt%) instead of Silicon, have also been compared with the predictions of this computing method, which are in good agreement with the experimental results (8-10% agreement for the final transformed fraction, and about 20-30% for the $t_{50\%}$ time).

Phase fractions and/or temperature estimation for a steel semi-product undergoing the steel processing operation

In the method for determining an amount of bainitic ferrite formed during a steel processing operation, that has been described above, the amount formed at each time step depends on the temperature T of the steel semi-product, which may evolve from one time step to the other (should this temperature be a local temperature at a given position in the steel semi-product, or an average temperature of the steel semi-product). In this regard, the temperature T of the steel, at the different times steps, may be:

- either, a known quantity, independent of the phases fractions f_α , f_γ , f_c , and that is acquired by a microstructure calculation module 15' that determines the temporal evolution of the phases fractions (case of figure 10); this is the case when a known, predetermined thermal path TP is imposed to the steel semi-product during the steel processing operation, for instance, or when the temperature of the steel semi-product being processed is measured all along the steel processing operation;
- or a quantity whose value is computed time step by step, along the steel processing operation, given an initial temperature T_i and heat exchanges between the steel semi-product and its environment (case of figure 11).

Figure 10 represents schematically steps executed to determine an amount of bainitic ferrite formed in a steel semi-product during a steel processing operation, according to the method that has been presented above (in the section "bainite formation").

As represented in figure 10, the microstructure calculation module 15' acquires the chemical composition CC of the steel and a value of the dimension d_γ of the austenite grains in the steel. The microstructure calculation module 15' also acquires data representative of the thermal path TP followed by the steel semi-product during the steel processing operation.

5 These data may specify the temperature imposed to the steel semi-product at each time step, during the processing operation. Alternatively, it may specify an initial temperature, duration, and final temperature for each of the successive phases composing the thermal path TP. The data representative of this thermal path TP may be acquired all at once, before the steel processing operation starts, or continuously, all along the processing operation (when the
10 temperature of the steel semi-product is measured online, several times successively during this processing operation, for instance).

As above mentioned, the microstructure calculation module 15' executes the set of steps s1, s2 and s3 several times successively, iteratively. At each execution of this set of steps, that is, for each new time step, the value of the temperature T, taken into account to
15 compute the evolution of the phase fractions f_α , f_γ , f_c , is the temperature, at that time step, according to the thermal path TP in question.

Figure 11 represents schematically steps executed to determine an amount of bainitic ferrite formed in a steel semi-product during a steel processing operation, for another embodiment of the method presented above, in the "bainite formation" section. In the
20 embodiment of figure 11, a microstructure calculation module 15 acquires the chemical composition CC of the steel and a value of the dimension d_γ of the austenite grains in the steel. The microstructure calculation module 15 also acquires the initial temperature T_i the steel has at the beginning of the steel processing operation (for instance at an input of a steel processing installation where the steel processing operation is achieved, or at an input of a given section
25 of this processing installation).

The microstructure calculation module 15 also acquires data representative of heating or cooling conditions HCC applied to the steel semi-product during the steel processing operation. These data specify operation conditions of heating or cooling devices of the steel processing installation, like the heating power output by heating elements such as radiant
30 tubes, or like the flow rate, speed and/or temperature of a coolant projected by one or more nozzles. Knowing these heating or cooling conditions HCC enables to determine the heat exchanges between the steel semi-product and its environment, during the steel processing operation. The data representative of the heating or cooling conditions HCC may be acquired all at once, before the steel processing operation starts, or continuously, all along the
35 processing operation.

In the embodiment of figure 11, the microstructure calculation module 15 determines the temperature T of the steel at the different time steps time step by time step, along the steel processing operation, taking into account:

- the initial value of the temperature, T_0 , and
- the heat exchanges between the steel semi-product and its environment, determined based on the heating or cooling conditions HCC.

Here, the temporal evolution of the temperature T is determined further taking into account the values, at each time step, of the phase fractions of bainitic ferrite, austenite and cementite, f_α , f_γ and f_C . More specifically, the heat capacity, and possibly the heat conductivity and/or density of the steel are determined based on the current values of f_α , f_γ and f_C . And, at each new time step, the microstructure calculation module 15 execute a step s4 (figure 11), to determine an updated value of the temperature T , based on:

- this (continuously updated) heat capacity,
- the above-mentioned heat exchanges, and
- a value of the temperature T at the previous time-step.

This arrangement enables to take into account the evolution of the heat capacity (and possibly conductivity) of the steel during the steel processing operation, caused by the phase transformations.

During step s4, the updated value of the temperature T may be determined taking also into account the variations of the phases fractions between the previous and next time step, more precisely taking into account the heat absorbed or released due to the variation of these phase fractions. This increases the accuracy of the determination of the temperature T , as the transformation of austenite into bainitic ferrite is exothermal. Regarding heat absorption/release due to cementite formation, it may generally be neglected.

As already mentioned, the microstructure calculation module 15 executes the set of steps s1, s2 and s3 several times successively, iteratively. In the case of figure 11, for each new time step, the microstructure calculation module executes:

- the set of steps comprising steps s1, s2 and s3,
- and, in parallel, step s4,

and then again (iteratively).

Still, the ensemble of steps s1 to s4 could be arranged differently. For instance, step s4 could be executed after step s3.

During the execution of steps s1 and s2, the value of the temperature T taken into account is the value determined during the last execution of step s4 (or, possibly, the initial temperature T_i , for the first execution of steps s1 and s2).

Both in the case of figure 10 and in the case of figure 11, the microstructure calculation module 15; 15 may be an electronic device comprising as least a processor and a memory,

and being configured, for instance programmed to execute the method for determining f_{α} , f_{γ} and f_C (and possibly T), as described above with reference to figure 10, or 11. The microstructure calculation module 15'; 15 may also take the form of a computer program or subprogram, that is a group of instructions whose execution on a computer (connected to
5 adequate sensors and/or communication channels) make the computer to execute the method described above with reference to figure 10 or 11.

Both in the case of figure 10 and figure 11, the initial temperature T_i acquired by the electronic device 15'; 15 may, like here, be a temperature that has been measured by a temperature sensor of the steel processing installation (like a pyrometer), and the evolution of
10 the phases fractions (and possibly of the temperature T) is then determined based on this measured temperature. Besides, the data representative of the thermal path TP followed by the steel semi-product (in the case of figure 10), or the data representative of the heating or cooling conditions HCC (in the case of figure 11) may also be data that are measured by
15 sensors of the steel processing installation (e.g.: steel temperature sensors, or coolant temperature sensors) and/or may be processing setpoints, transmitted to the heating or cooling devices of the installation by an electronic control apparatus of this installation. The method for determining the amount of bainitic ferrite formed during the steel processing operation can then be considered as a non-direct measurement method, for non-directly measuring or
20 predicting the phases fractions f_{α} , f_{γ} and f_C and/or for non-directly measuring or predicting the temperature T of the steel semi-product. Indeed, these quantities are then deduced from one or more measurements relative to the steel semi-product and possibly, relative to the process operation.

This non-direct measurement, or prediction, of f_{α} , f_{γ} , f_C and/or T may be employed to monitor the steel processing operation (typically in real time), in which case the value of at
25 least one of f_{α} , f_{γ} , f_C and T, at least one of the time steps, is transmitted by the microstructure calculation module 15; 15' to a human-computer interface such as a display screen, to be output (eg: to be displayed to an operator); for instance, final values of f_{α} , f_{γ} , f_C (or a final value of T), at the end of the steel processing operation, predicted according to said method, are displayed on a display screen, and are continuously updated each time a new semi-product
30 is input, or each time a new section of a same steel strip enters the steel processing installation.

The non-direct measurement, or prediction, of f_{α} , f_{γ} , f_C and/or T mentioned above may also be employed to characterize the steel semi-product having been processed. In this case final values of f_{α} , f_{γ} , f_C (or a final value of T), at the end of the steel processing operation, determined according to said method, are output by the microstructure calculation module 15;
35 15' and transmitted to a production database in which they are recorded.

The non-direct measurement, or prediction, of f_{α} , f_{γ} , f_C and/or T mentioned above may also be employed for controlling the steel processing installation, during the steel processing operation itself, as detailed in the next section “process control”.

5 Process control

One of the possible control methods for controlling the steel processing operation, based on the values of f_{α} , f_{γ} , f_C and/or T determined as above explained, is the control method described below, in which a kind of feed-forward control is implemented. In this control method,
10 an electronic control apparatus, including the microstructure calculation module 15; 15’:

- acquires the initial temperature T_i ,
- acquire planned process parameters, intended to be employed during the steel processing operation; said process parameters are either representative of a planned thermal path TP or of planned heating or colling conditions HCC,
- 15 - determine an estimated final property of the steel semi-product at the end of steel processing operation; said property is either the temperature of the steel semi-product, its phases content (that is the values of f_{α} , f_{γ} , f_C), or a mechanical property determined based on its phases content, like its tensile strength or yield strength; said property is determined by computing final values of f_{α} , f_{γ} , f_C , or of T as
20 explained above in section “phase fractions and/or temperature estimation”,
- compare the estimated final property with a target final property, desired at the end of the processing operation,
- adjust the process parameters depending on said comparison,
- control the heating or cooling devices of the steel processing installation based on
25 the process parameters thus adjusted.

In an embodiment of this control method, described in more details below with reference to figure 12, the property in question is the temperature T of the steel semi-product, which is steel strip 1, and the process parameters in question are cooling conditions, specifying operating conditions of valves 8, 9 that control cooling jets 21 of a Run-Out-Table.

30 Figure 12 schematically represents a hot-rolling installation for delivering a hot-rolled steel strip 1, which includes a furnace 2, a rolling mill 3 and a cooling apparatus 4 (namely the Run-Out-Table), for cooling the steel strip 1. The hot-rolling installation comprises also an electronic control apparatus 5 for controlling the cooling apparatus 4.

The strip 1 is for example a steel plate having a thickness comprised between 1 mm
35 and 30 mm.

The steel strip 1, on discharge from the furnace 2 and the rolling mill 3, is moved in a running direction A. In this example, the running direction A of the strip 1 is substantially horizontal. The strip 1 then passes through the cooling apparatus 4, in which the strip is cooled from its initial temperature T_i down to a final temperature (which is for example room temperature, i.e. about 20°C, but that may also be higher, the end of the cooling occurring once the strip is coiled). The initial temperature T_i is for example substantially equal to the temperature at the end of the rolling of the strip. T_i is measured using a pyrometer 24 connected to the control apparatus 5. The initial temperature T_i is for example greater than or equal to 600°C, notably greater than or equal to 800°C, or even greater than 1000°C. The strip 1 passes through the cooling apparatus 4 in the running direction A at a running speed which is preferably comprised between 1 m/s and 25 m/s.

In the cooling apparatus 4, at least one first cooling fluid jet 21 is ejected on a top surface of the strip 1, and at least one second cooling fluid jet is ejected on a bottom surface of the strip 1, opposite its top surface. The cooling fluid, also called coolant, is for example water. The cooling apparatus 4 comprises top and bottom valves, 8 and 9, configured for opening or closing the coolant flow in the direction of the steel strip 1.

The electronic control apparatus 5 includes:

- the microstructure calculation module 15 of figure 11, and
- a control module 14, configured for controlling the cooling apparatus 4 according to the temperature T (in particular the final temperature) determined by the microstructure calculation module 15.

The electronic control apparatus 5 is configured for determining the flow for each valve 8, 9, and accordingly for determining which valve 8, 9 needs to be turned on or off. For example, based on a given cooling pattern, the position of the pyrometer 24 and the target temperature, the control module 14 determines which valves 8, 9 need to be turned on or off in order to compensate for initial temperature variation and strip speed variation.

In this example, the microstructure calculation module 15 is configured so that, when determining the evolution of the temperature T and phases content of the strip, the heat exchanges between the strip 1 and its environment are computed according to the formulas presented in paragraphs 55 to 102 of document EP3645182A1, more specifically according to paragraphs 79, 84, 87, 90 and 93. The evolution of the temperature T of the strip is determined as presented above with respect to figure 11. So, it may, in particular, be determined as described in paragraphs 55 to 102 of document EP3645182A1, but replacing the phase transformation calculation described in paragraph 101 of EP3645182A1 by the phase transformation calculation above presented in section "bainite formation", or, possibly, completing the phase transformation calculation described in paragraph 101 of EP3645182A1 with the bainite formation calculation in question.

Figures 13 and 14 represent production data recorded when operating the cooling apparatus 4, either using the control method that has just been described (curve 13b, histogram 14b), or using the prior art control method described in EP3645182A1 (curve 13a, histogram 14a).

Figure 13 shows two comparative curves 13a, 13b, regarding the percentage of coils that are provided within a defined tolerance on a coiling temperature error, said defined tolerance being indicated on abscissa axis. Said coiling temperature is the final temperature, at the end of the steel processing operation. Curve 13b illustrates the results of the method according to the invention while curve 13a shows the results of the prior art method (of EP3645182A1). The results with the method according to the invention are better than the ones with the prior art method, since for any value of the defined tolerance indicated on abscissa axis, the percentage of provided coils within said defined tolerance is better with the method according to the invention than with the prior art method.

Figure 14 shows two comparative histograms 14a, 14b indicating the number of coils that are provided for a respective gap between the target coiling temperature and the measured coiling temperature, said gap being indicated on abscissa axis. Histogram 14b illustrates the results of the method according to the invention while histogram 14a shows the results of the prior art method (of EP3645182A1). The results with the method according to the invention are better than the ones with the prior art method, since histogram 14b is better centred onto zero than histogram 14a, and has values higher than histogram 14a for the small values of the gap (for gap values between -20 and +20°C).

Figures 13 and 14 gather production data obtained coils having each a chemical composition CC within the following ranges (in weight%): C_o : [0.065 ; 0.1] , x_{Mn} = [1.3 ; 1.6] , x_{Si} = [0.01 ; 0.15], x_{Ni} = [0.025 ; 0.05] , x_{Cr} : [0.02 ; 0.04] , x_{Nb} : [0.03 ; 0.05].

For instance, for one of the coils of figures 13 and 14, the chemical composition was: C_o = 0.1 , x_{Mn} = 1.5 , x_{Si} = 0.09 , x_{Al} = 0.04 , x_{Ni} = 0.03 , x_{Cr} = 0.04 , x_{Nb} = 0.03, the rest being iron and unavoidable impurities.

Improvements similar, or even higher to those of figures 13 and 14 have also been observed with other grades. For instance, for a grade corresponding to the following ranges: C_o : [0.05 ; 0.06] , x_{Mn} = [1.4 ; 1.5] , x_{Si} = [0.2 ; 0.25], x_{Ni} = [0.025 ; 0.035] , x_{Cr} : [0.3 ; 0.35] , x_{Nb} : [0.025 ; 0.035].

And also for a grade corresponding to the following ranges: C_o : [0.05 ; 0.07] , x_{Mn} = [1.8 ; 1.9] , x_{Si} = [0.02 ; 0.04], x_{Ni} = [0.025 ; 0.045] , x_{Cr} : [0.02 ; 0.028] , x_{Nb} : [0.06 ; 0.08] , x_{Nb} : [0.06 ; 0.08], x_{Ti} : [0.1 ; 0.15].

A method for controlling the coolant jets in a Run-Out-Table, wherein bainite formation is taken into account according to the method presented above (in section “bainite formation”) has just been described.

Still, other steel processing operations can be controlled, according to the invention, using values of f_{α} , f_{γ} , f_C and/or T that are determined according to the methods presented above in the section “bainite formation” or in the section “Phase fractions and/or temperature estimation”. For instance, a thermal treatment operation, that follows an annealing, and that includes or precedes a coating operation like a hot-dip coating operation, may be controlled as above explained, in order to obtain a target fraction of bainite at the end of the operation.

Computer Assisted Design of a steel processing operation

The method for determining an amount of bainitic ferrite formed during a steel processing operation (described in the section “bainite formation”) can also be used for determining, in a Computer Aided Design way, a thermal path to be followed by a steel semi-product in order to obtain a given target property at the end of said processing. Said target property can be:

- a target mechanical property, like a tensile or yield strength, deduced from the phase fractions f_{α} , f_{γ} , f_C ,
- or the phase fractions f_{α} , f_{γ} , f_C themselves.

This thermal path can be determined, for instance, by executing the method of figure 10 several times, for different candidate thermal paths, and then selecting the candidate thermal path that leads to a final property, at the end of the steel processing operation, that is the closest to the target property aimed at. Alternatively, a candidate thermal path can be adjusted iteratively, by gradually modifying the thermal path (the method of figure 10 being executed at each iteration) until leading to a final property close enough (i.e.: within a given precision range) to the target property. Other schemes for determining (or, in other words optimizing) such a thermal path can also be employed.

Once the thermal path leading to said target property (within a given precision range) is identified, the steel processing operation is executed according to this thermal path.

The determination of such a thermal path, and then control of a steel processing installation accordingly, can be executed by an electronic device or system configured to this end.

CLAIMS

1. A method for determining an amount of bainitic ferrite (f_α) formed in a steel semi-product (1) during a steel processing operation, the steel semi-product having a chemical composition CC, the method comprising the following steps, executed by an electronic device:
 - Acquiring the chemical composition CC of the steel of said steel semi-product,
 - s1) determining a bainitic ferrite growth rate, as being proportional to:
 - o a density of bainitic ferrite nucleation centers ($n_{nuct,\alpha}$),
 - o $\exp(-Q^*/RT)$ where T is the temperature of the steel, R is the universal gas constant and Q^* is an activation energy for an austenite to bainitic ferrite transformation, and to
 - o a moderation coefficient, which approaches zero when a free enthalpy of a bainitic ferrite phase approaches a free enthalpy of an austenite phase, the enthalpy of the austenite phase depending at least on a Carbon content (C^γ) in said phase,
 - s2) determining a cementite growth rate, depending at least on the chemical composition CC of the steel and on the Carbon content (C^γ) in the austenite phase,
 - s3) determining values at a next time step for bainitic ferrite, austenite and cementite phases fractions (f_α , f_γ , f_C), based on the bainitic ferrite growth rate and on the cementite growth rate, and determining a value at the next time step for the Carbon content in the austenite phase (C^γ) based on the values of said phases fractions (f_α , f_γ , f_C),

the set of steps s1, s2 and s3 being executed several times successively.
2. A method according to claim 1 wherein the moderation coefficient:
 - is proportional to $|\Delta G_{\gamma \rightarrow \alpha}|/RT$ when $|\Delta G_{\gamma \rightarrow \alpha}|/RT$ approaches zero, $\Delta G_{\gamma \rightarrow \alpha}$ being the difference between the free enthalpy of the bainitic ferrite phase and the free enthalpy of the austenite phase, and
 - is bound to a constant value when $|\Delta G_{\gamma \rightarrow \alpha}|/RT$ increases.
3. A method according to claim 2 wherein the moderation coefficient is equal or substantially equal to $\tanh(|\Delta G_{\gamma \rightarrow \alpha}|/RT)$.
4. A method according any of the preceding claims wherein Q^* is equal or substantially equal to $Q_0 + K_1 \cdot |\Delta G_{\gamma \rightarrow \alpha}|$, where $\Delta G_{\gamma \rightarrow \alpha}$ is the difference between the free enthalpy of the bainitic ferrite phase and the free enthalpy of the austenite phase, and where Q_0 and K_1 depend on the chemical composition CC of the steel but do not vary when the Carbon content (C^γ) in the austenite phase evolves, during said processing.

5. A method according to claim 4 wherein Q_o is equal or substantially equal to $A+B.(T-T_M)$, A and B being two constants and T_M being the Martensite start temperature for said steel.
6. A method according to any of the preceding claims wherein the density of bainitic ferrite nucleation centers ($n_{nucl,\alpha}$) is equal or substantially equal to:
 - an overcooling T_B-T , where T_B is the Bainite start temperature, multiplied by
 - a coefficient α^b , that depends on the chemical composition CC of the steel and that is proportional to $1/d_\gamma$, d_γ being a dimension of austenite grains in said steel.
7. A method according to any of the preceding claims wherein the bainitic ferrite growth rate is computed according to equation eqn 1 below

$$\frac{d f_\alpha}{dt} = v \cdot n_{nucl,\alpha} \cdot f_\gamma \cdot (1 + \lambda f'_\alpha) \cdot \exp(-Q^*/RT) \cdot C_{mod} \quad (eqn 1)$$

where

- f_α is the fraction of bainitic ferrite in said steel,
 - C_{mod} is the moderation coefficient,
 - $n_{nucl,\alpha}$ is the density of bainitic ferrite nucleation centers,
 - $v = kT/h \approx 10^{13} s^{-1}$,
 - f'_α is equal to f_α , or possibly to $f_\alpha + f_F$, f_F being the fraction of ferrite in said steel,
 - f_γ being the fraction austenite in said steel,
 - and λ is an auto-catalysis coefficient proportional to a dimension d_γ of austenite grains.
8. A method according to any of the preceding claims wherein the cementite growth rate is kept equal to zero as long as the Carbon content (C^γ) in the austenite phase remains below a Carbon content threshold for cementite precipitation ($C^{\gamma \rightarrow c}$) which depends on the chemical composition CC of the steel.
 9. A method according to any of the preceding claims wherein the Carbon content (C^γ) in the austenite phase is computed while neglecting a Carbon content in the bainitic ferrite phase (C^α) with respect to the Carbon content (C^γ) in the austenite phase, and with a carbon content in the cementite phase (C^c) that is constant.
 10. A method according to any of the preceding claims wherein Carbon, Manganese, Silicon, Aluminum and Chromium contents in said steel, noted respectively as C_o , x_{Mn} , x_{Si} , x_{Al} and x_{Cr} and expressed in weight %, are in the following ranges: $C_o \leq 0.5$; $x_{Mn} \leq 3$; $x_{Si} \leq 2$; $x_{Al} \leq 1.5$; $x_{Cr} \leq 4$.
 11. A method for monitoring a steel processing operation during which a steel semi-product (1) is processed in a steel processing installation (4), the method comprising the following steps:

- Acquiring at least an initial temperature (T_i) of the steel semi-product at beginning of the steel processing operation, said temperature being measured by a sensor (24) of the steel processing installation,
- Determining an amount of bainitic ferrite (f_α) formed in the steel semi-product during the steel processing operation, according to the method of any of claims 1 to 10, said method for determining being executed while taking into account that the steel temperature at the beginning of the steel processing operation is the initial temperature (T_i) measured by said sensor.

12. A method according to claim 11, further comprising

- Acquiring thermal path data, representative of a thermal path (TP) followed by the steel semi-product during the steel processing operation,

And wherein, when determining the amount of bainitic ferrite formed according to the method of any of claim 1 to 10, at each stime step, the evolution of the bainitic ferrite phase fraction is determined taking into account a temperature (T) of the steel according to said thermal path.

13. A method according to claim 11, further comprising:

- Acquiring data representative of heating or cooling conditions (HCC) applied to the steel semi-product (1) during the steel processing operation,

And wherein, when determining the amount of bainitic ferrite formed according to the method of any of claim 1 to 10, at each stime step, an updated value of the temperature (T) of the steel is determined taking into account said heating or cooling conditions and taking into account the respective phase fractions of bainitic ferrite, austenite and cementite (f_α , f_γ , f_C) in said steel.

14. A method according to claim 13, wherein heating or cooling actuators (8, 9) of the steel processing installation (4) are controlled depending on:

- a temperature (T) of the steel expected at an end of the steel processing operation, as determined according to claim 13, and depending on
- a target temperature, to be reached by the steel semi-product (1) at the end of the steel processing operation.

15. A method according to any of claims 11 to 13, wherein

- An estimated final property of the steel semi-product is determined, taking into account the amount of bainitic ferrite formed during the steel processing operation, and
- process parameters are adjusted, depending on said estimated final property and depending on a target property for the steel semi-product (1), to be obtained at the end of the steel processing operation, the process parameters thus adjusted being

transmitted to actuators (8, 9) of the steel processing installation for achieving the steel processing operation according to said process parameters.

16. A method according to any of claims 11 to 15, wherein at least one value of the bainitic ferrite fraction determined during said method for determining is output using a human-computer interface, or is recorded in a production database.

17. A method for controlling a steel processing installation, the method comprising the following steps:

- Determining a thermal path, to be followed by the steel semi-product during the steel processing operation, in order to obtain a given target property for the steel semi-product at an end of said processing, said thermal path being determined taking into account bainitic ferrite formation during said processing, an amount of bainitic ferrite formed during said processing being determined according to the method of any of claim 1 to 10,

- Controlling actuators of the steel processing installation for achieving the steel processing operation according to the thermal path determined.

18. An electronic device (15 ; 15' ; 5) comprising at least a processor and a memory, configured for executing the method according to any of claims 1 to 17.

19. A computer program, comprising instructions whose execution on a computer make the computer to execute the method according to any of claims 1 to 17.

FIG 1

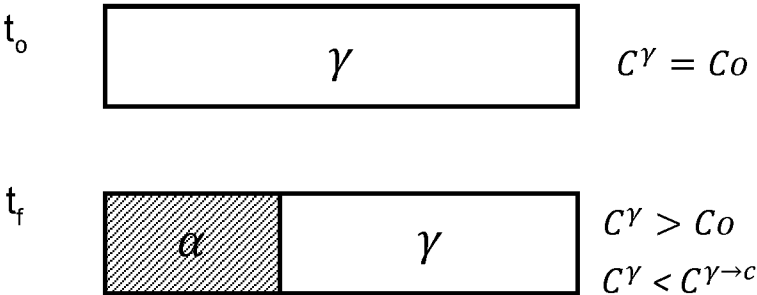


FIG 2

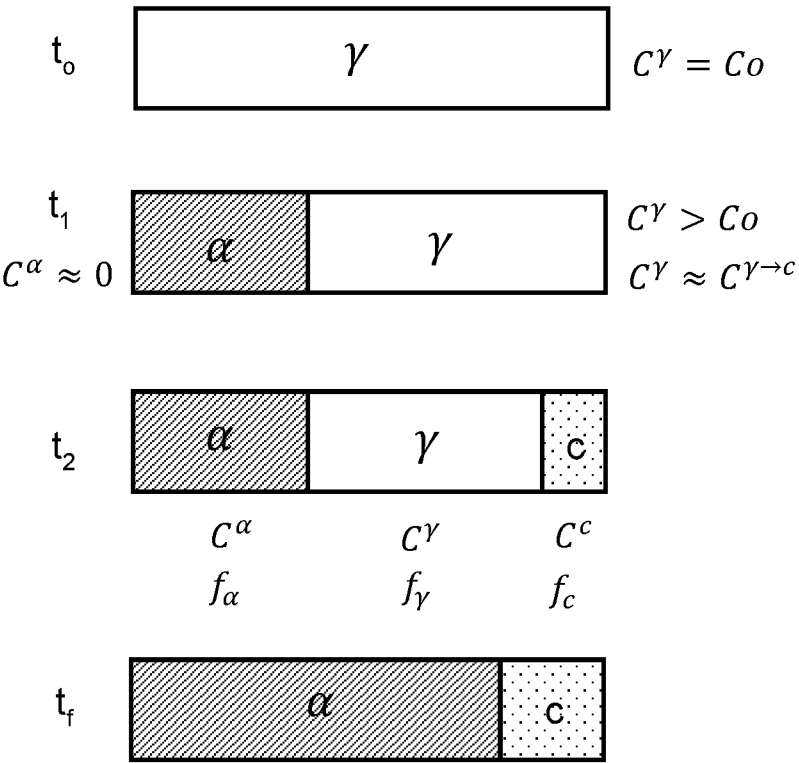


FIG 3

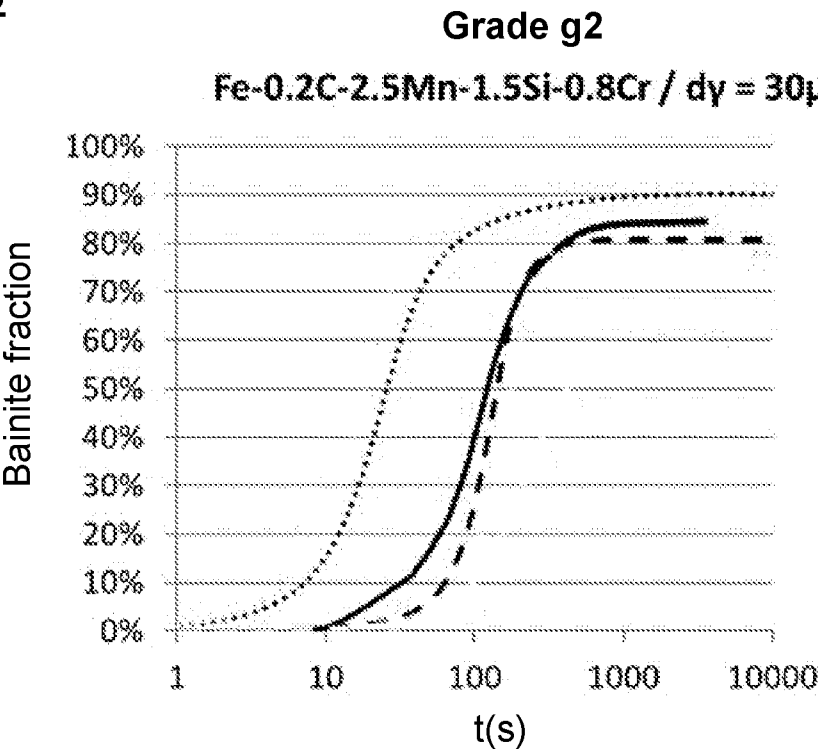


FIG 4

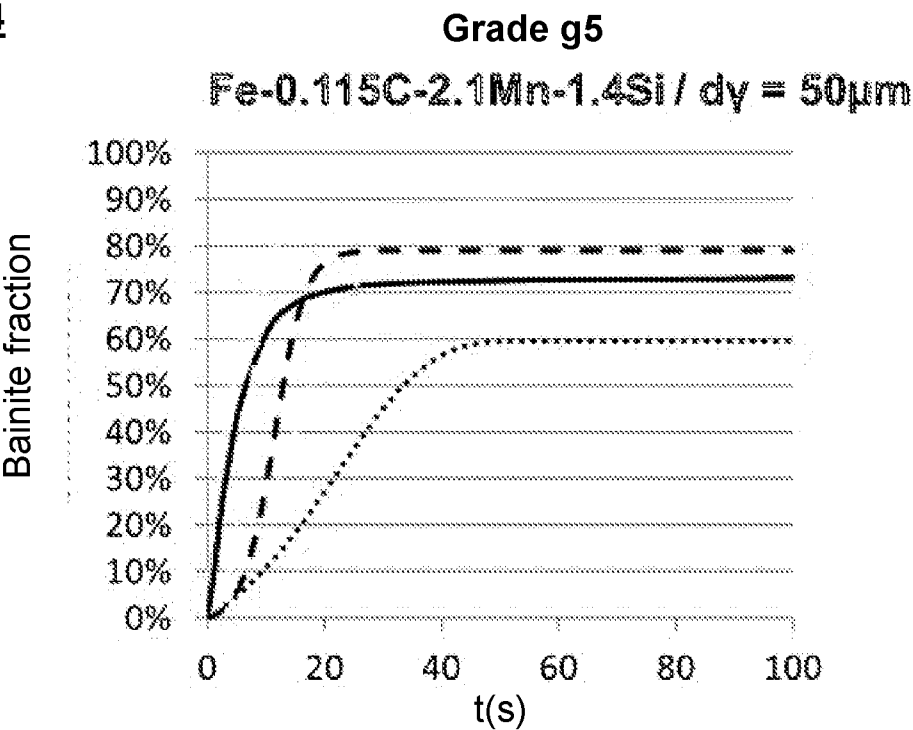


FIG 5

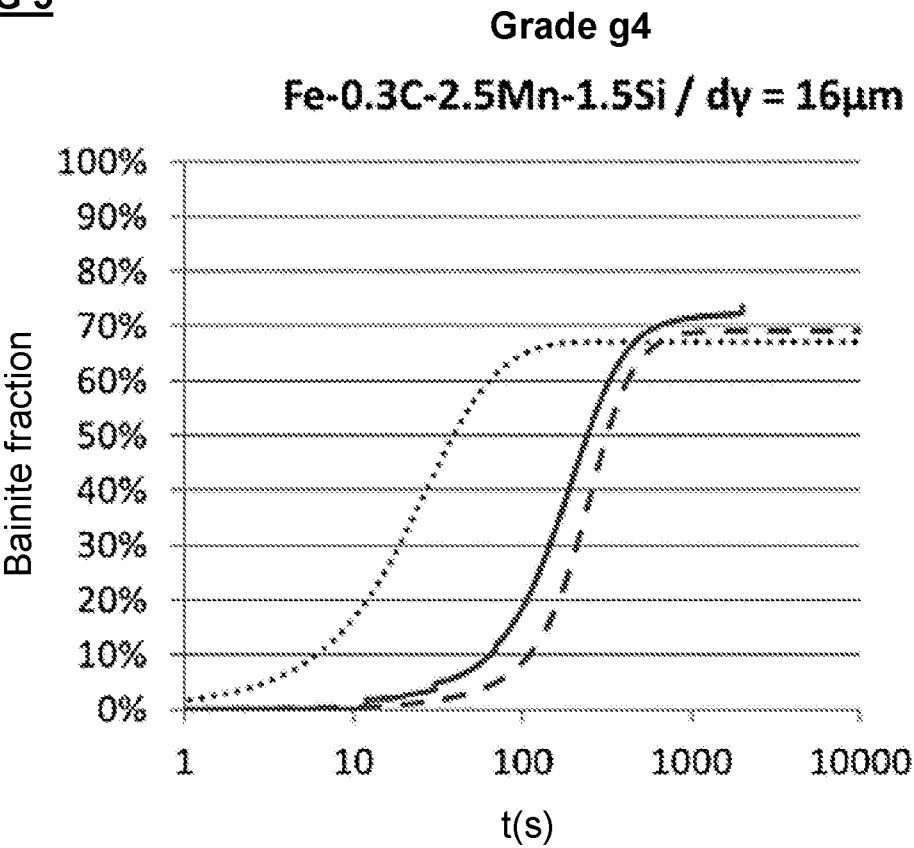


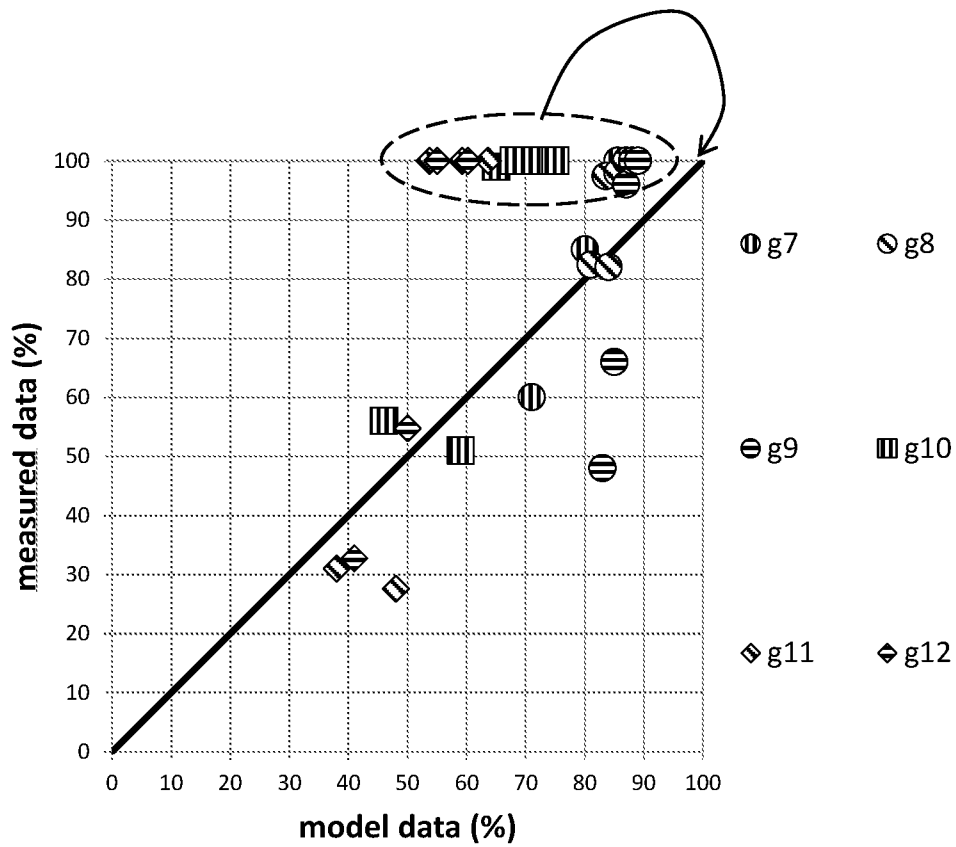
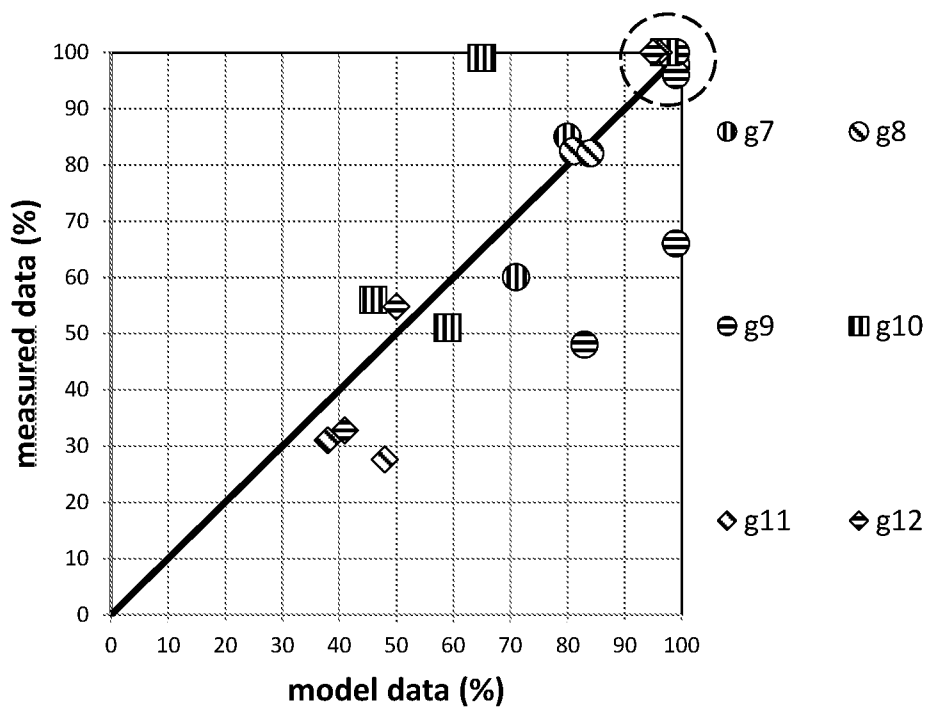
FIG 6**FIG 7**

FIG 8

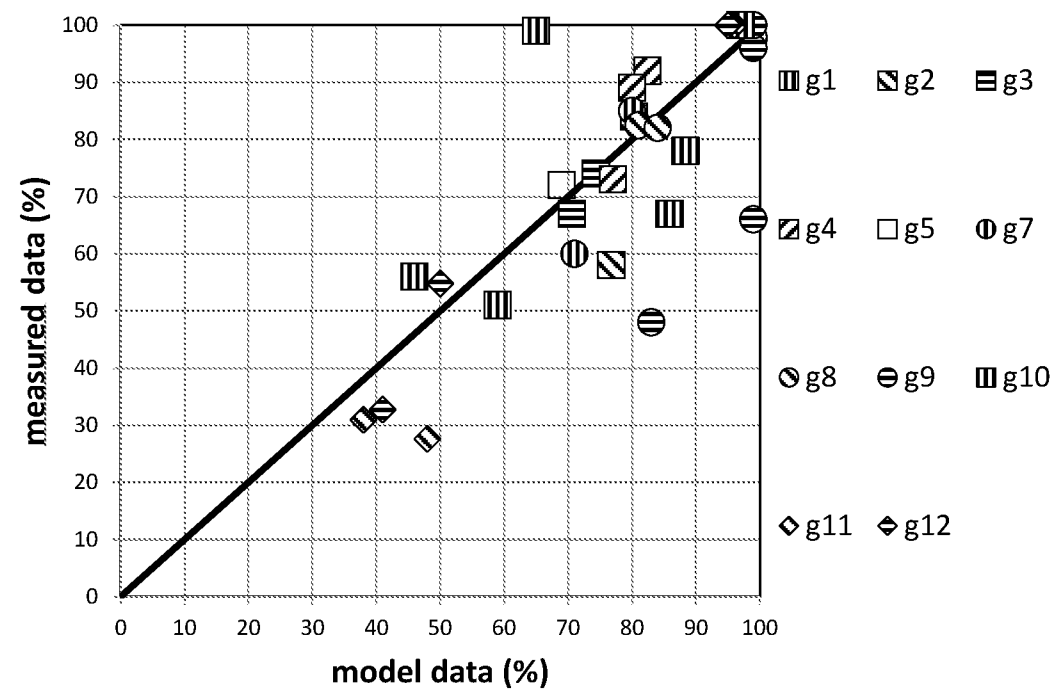


FIG 9

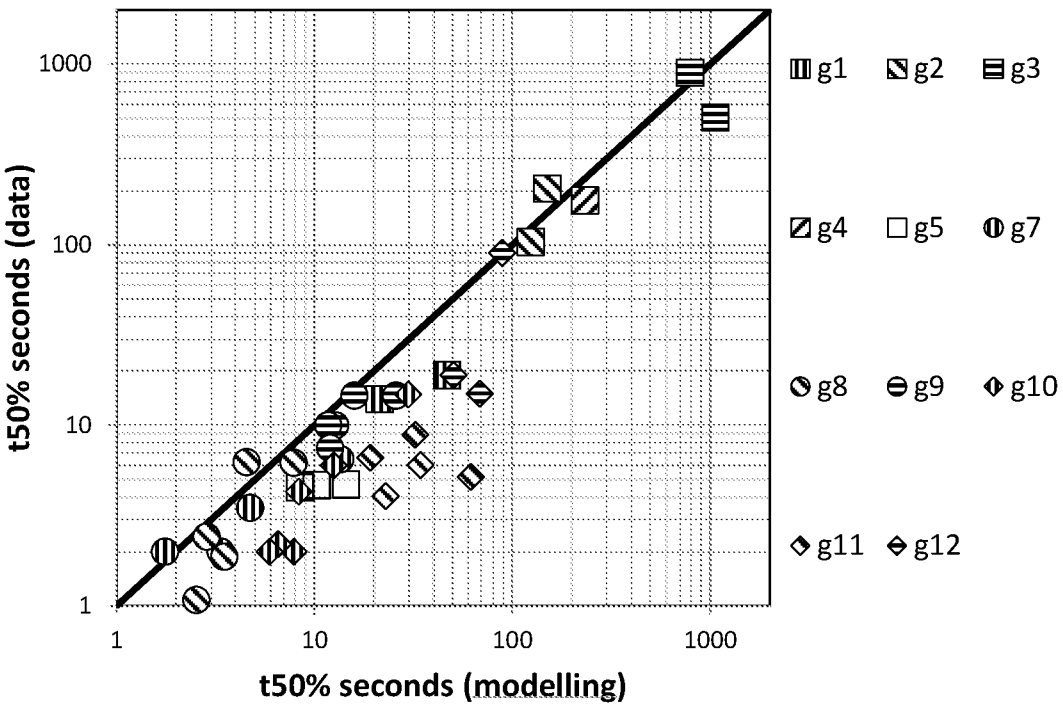
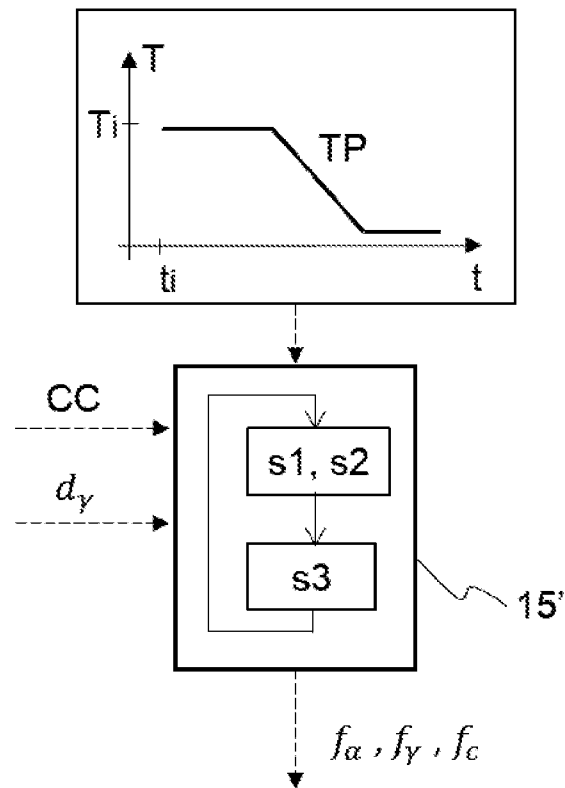
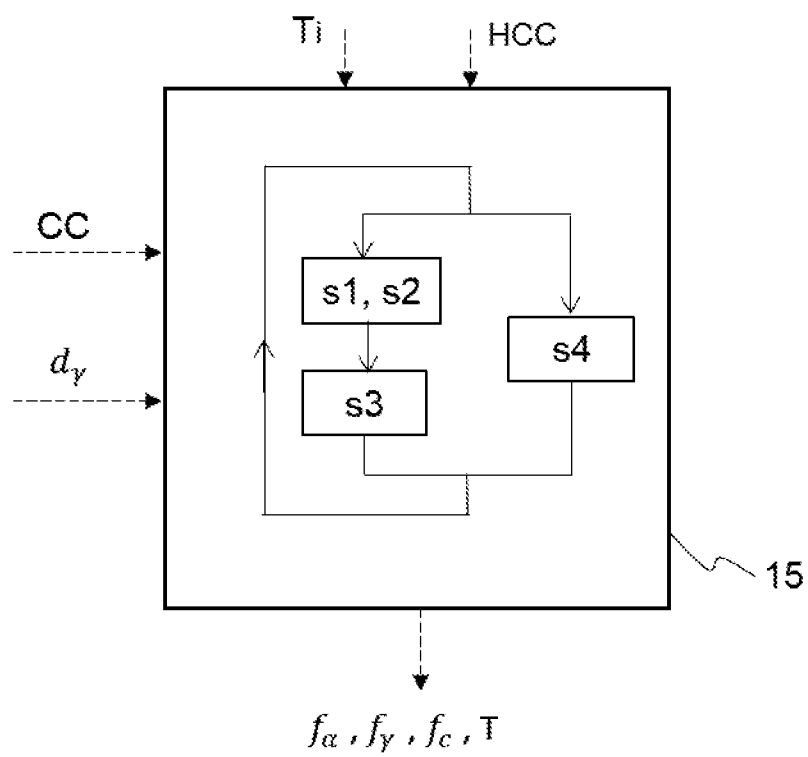


FIG 10**FIG 11**

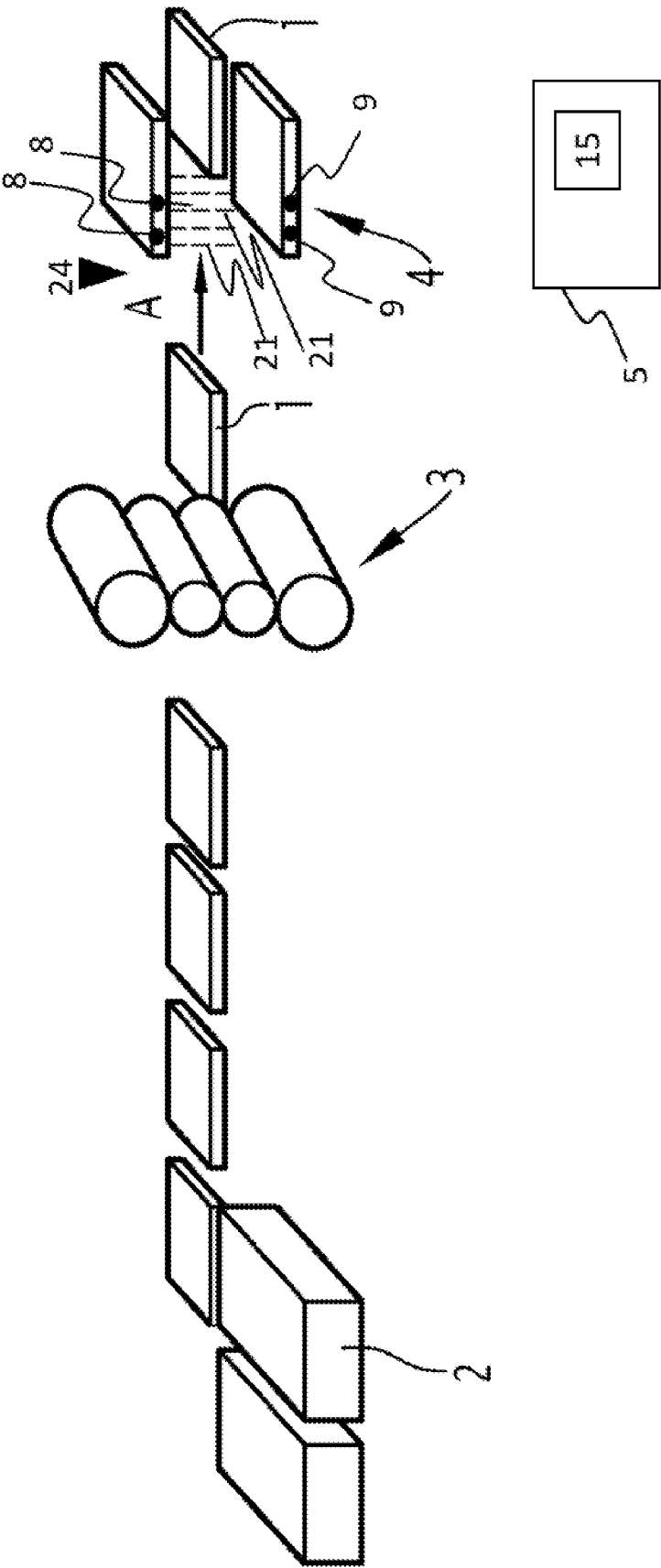
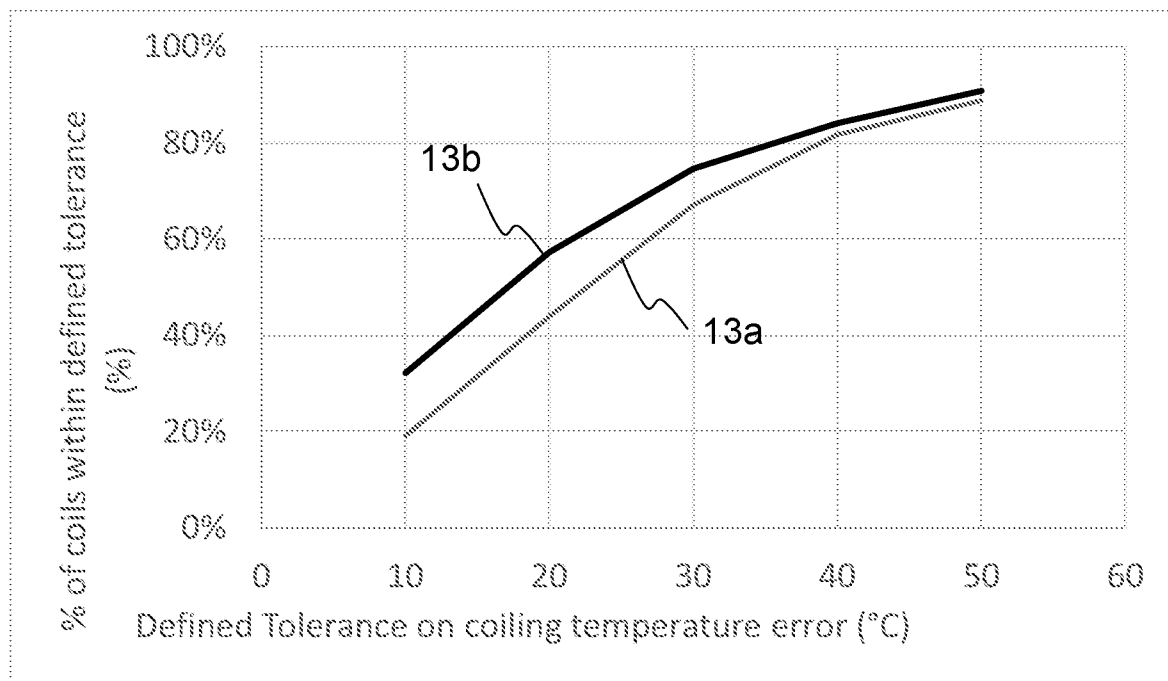
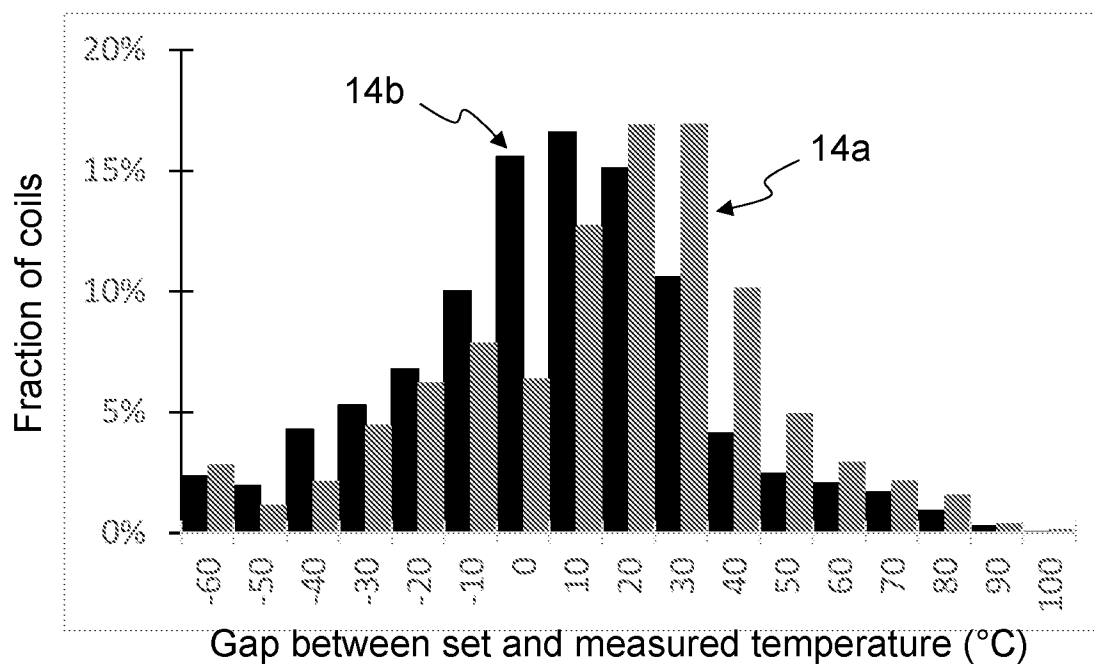


FIG 12

FIG 13**FIG 14**

INTERNATIONAL SEARCH REPORT

International application No

PCT/IB2023/056772

A. CLASSIFICATION OF SUBJECT MATTER INV. C21D6/00 C21D11/00 G16C10/00 G16C60/00 ADD.		
According to International Patent Classification (IPC) or to both national classification and IPC		
B. FIELDS SEARCHED Minimum documentation searched (classification system followed by classification symbols) C21D G16C		
Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched		
Electronic data base consulted during the international search (name of data base and, where practicable, search terms used) EPO-Internal		
C. DOCUMENTS CONSIDERED TO BE RELEVANT		
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	Fazeli Fateh ET AL: "Modelling Simultaneous Formation of Bainitic Ferrite and Carbide in TRIP Steels", ISIJ International, 1 January 2012 (2012-01-01), pages 650-658, XP093116422, DOI: 10.2355/isijinternational.52.650 Retrieved from the Internet: URL:https://www.jstage.jst.go.jp/article/isijinternational/52/4/52_4_650/_pdf [retrieved on 2024-01-06] Section 2 Section 3, 3.2, 3.3, 3.4, 3.6 Section 4 ----- -/--	1-19
☒ Further documents are listed in the continuation of Box C. ☐ See patent family annex.		
* Special categories of cited documents : "A" document defining the general state of the art which is not considered to be of particular relevance "E" earlier application or patent but published on or after the international filing date "L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified) "O" document referring to an oral disclosure, use, exhibition or other means "P" document published prior to the international filing date but later than the priority date claimed "T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention "X" document of particular relevance;; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone "Y" document of particular relevance;; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art "&" document member of the same patent family		
Date of the actual completion of the international search 8 January 2024		Date of mailing of the international search report 16/01/2024
Name and mailing address of the ISA/ European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3016		Authorized officer Neibecker, Pascal

INTERNATIONAL SEARCH REPORT

International application No

PCT/IB2023/056772

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT		
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	VAN BOHEMEN STEFAN M. C. ET AL: "Modeling of isothermal bainite formation based on the nucleation kinetics", INTERNATIONAL JOURNAL OF MATERIALS RESEARCH., [Online] vol. 99, no. 7, 23 May 2013 (2013-05-23), pages 739-747, XP093116338, DE ISSN: 1862-5282, DOI: 10.3139/146.101695 Retrieved from the Internet: URL:https://dx.doi.org/10.3139/146.101695> Section 2 -----	1-19
A	VAN BOHEMEN S.M.C.: "Modeling Start Curves of Bainite Formation", METALLURGICAL AND MATERIALS TRANSACTIONS A, [Online] vol. 41, no. 2, 2 December 2009 (2009-12-02), pages 285-296, XP093116423, New York ISSN: 1073-5623, DOI: 10.1007/s11661-009-0106-9 Retrieved from the Internet: URL:https://link.springer.com/content/pdf/10.1007/s11661-009-0106-9.pdf> Section II -----	1-19